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Applied Research in Statistics - Mathematics - Operations Research

AN EXAMINATION OF STATISTICAL
IMPACT ACCELERATION INJURY PREDICTION
MODELS BASED ON TORQUE AND FORCE VARIABLES

by

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See 1473 in back

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I. INTRODUCTION

Two previous Desmatics technical reports [3, 5] discussed impact acceleration injury prediction model development and estimation accuracy respectively. Another technical report [4] described the construction of impact acceleration injury prediction models from a set of twenty-eight $-G_x$ accelerator runs involving Rhesus monkeys with securely restrained torso and unrestrained head. The models described in that report employed head dynamic response variables and sled profile variables as injury predictors.

This report considers the application of such models to the same twenty-eight $-G_x$ acceleration run data set described in [4], but with torque and force variables as possible injury predictors. The purpose of this report is to determine whether the forces or torques experienced during these runs can be used to predict injury probability.

The models under consideration are based on the assumption of an underlying functional relationship of the form

$$P(\underline{x}) = \{1 + \exp[-(\beta_0 + \sum_{1}^{k} \beta_i x_i)]\}^{-1}$$

where:

$\underline{x} = (x_1, \ldots, x_k)$ denotes the set of independent variables considered,

$(\beta_0, \ldots, \beta_k)$ denotes a set of parameter values,

and $P(\underline{x})$ denotes the true probability of injury corresponding to $\underline{x}$. The torque and force variables used in this investigation were:

(1) peak torque around the anatomical Y axis,

(2) peak force along the anatomical X axis,

and (3) peak force along the anatomical Z axis.

These three variables were investigated in a preliminary study conducted by Lustick and Shimp [1].

The statistical analysis used in constructing the impact acceleration injury prediction models indicates that, of the three variables considered, the peak force along the anatomical Z axis correlates most highly with injury. In five of the six cases where injury occurred, this force was 76.5 kilograms or larger.

II. MODEL CONSTRUCTION

The data base used in model construction consisted of twenty-eight $-G_x$ accelerator runs on Rhesus monkeys. The experimental runs are the same ones as in technical report [4], but here different impact acceleration injury predictors are used. Because some monkeys were run more than once, dependence exists in the data. It will be assumed, however, that the effects of dependence are small. In any event, the dependence in the data will be responsible for a slightly conservative model, i.e., one that would predict probabilities of injury that are biased upward.

Since it is difficult to define injury, fatality was the criterion used in development of the models discussed in this report. So in actuality these models are fatality prediction models. The complete data set is given in Figure 1. In this figure a 1 represents a fatal run and a 0 represents a nonfatal run.

It should be noted that most fatalities involved a transection in the region between the lower medulla and upper cervical spinal cord. (See [7] for a further discussion of the neuropathological findings.) This is where the torque and force variables were measured. Thus, the models in this report are used to predict fatality from torques and/or forces at the site of the injury.

A. ESTIMATION OF MODEL PARAMETERS

A computer program for maximum likelihood estimation was used to calculate $\hat{\beta}_0, \hat{\beta}_1, \ldots, \hat{\beta}_k$, i.e., the estimates of the parameters $\beta_0, \beta_1, \ldots, \beta_k$. In model construction, it is possible that some or all of the candidate

Run Number	Subject Number	Observed Probability	Peak Torque Around Anatomical Y Axis	Peak Force Along Anatomical X Axis	Peak Force Along Anatomical Z Axis
LX1081	A03921	0	-0.19	-7.1	-0.8
LX1082	A03921	0	-0.87	-32.0	-14.5
LX1083	A03921	0	-0.85	-32.5	-9.2
LX1084	A03921	0	-0.75	-27.3	-14.5
LX1085	A03921	0	-0.85	-32.0	-13.5
LX1086	A03921	0	-0.85	-32.0	-11.6
LX1087	A03921	0	-0.96	-36.0	-14.5
LX1364	A03921	0	-0.88	-32.5	-16.0
LX1365	A03921	1		-130.0	-82.0
LX1359	A04099	0	-3.60	-132.0	-46.0
LX1360	A04099	1	-3.40	-132.0	-124.0
LX1362	A03935	0	-5.20	-200.0	-45.0
LX1363	A03935	1	-2.50	-92.0	-48.0
LX1889	A04101	0	-1.60	-47.5	-20.0
LX1890	A04101	0	-0.73	-27.5	-13.7
LX1898	A04101	0	-0.85	-32.0	-10.0
LX1899	A04101	0	-0.76	-28.5	-9.0
LX1900	A04101	0	-1.93	-72.0	-32.0
LX1901	A04101	0	-2.23	-82.0	-37.0
LX1902	A04101	0	-2.15	-82.0	-45.0
LX1903	A04101	0	-2.60	-97.0	-48.0
LX1905	A04101	1	-3.70	-140.0	-76.5
LX1891	A03943	0	-1.80	-65.0	-40.0
LX1892	A03948	0	-1.75	-68.0	-32.0
LX1893	A03924	0	-2.90	-105.0	-71.0
LX1894	A03933	0	-2.10	-83.0	-72.0
LX1895	A03951	1	-2.00	-80.0	-86.0
LX1896	A03946	1	-3.00	-113.0	-92.0

Figure 1: The Data Set

variables may prove unimportant and should therefore not be included in a final model. The contribution of variables may be discerned by likelihood-ratio tests. These tests may be used in conjunction with "nested" models.

In this technical report, one model will be said to be nested within another if the second model contains all variables of the first model plus one or more additional variables. Thus, a model which contained variables x_1, x_2, and x_3 would be nested within a model which contained only x_1 and x_2. To test a hypothesis that a model containing variables $(x_1,\ldots,x_{k+m})$ is a statistically significant improvement over a model containing variables $(x_1,\ldots,x_k)$, a log-likelihood statistic may be used. The procedure is to calculate:

L_1 = -2 log likelihood for the model containing $(x_1,\ldots,x_k)$

and L_2 = -2 log likelihood for the model containing $(x_1,\ldots,x_{k+m})$.

Under the null hypothesis that the m additional variables $(x_{k+1},\ldots,x_{k+m})$ do not result in an improved model, the statistic $L_1 - L_2$ has an approximate Chi-square distribution with m degrees of freedom. Thus, the hypothesis may be tested by comparing the value of $L_1 - L_2$ with the upper percentage points of a Chi-square distribution with m degrees of freedom.

B. TORQUE AND FORCE VARIABLES

As mentioned in the introduction, three fatality predictors were considered for model development. These variables will be denoted by THB, FHA, and FHC (as defined by Lustick and Shimp [1]), where:

THB is the peak torque around the anatomical Y axis,

FHA is the peak force along the anatomical X axis, and FHC is the peak force along the anatomical Z axis.

Model construction was somewhat complicated by two aspects of the data set. First, the torque variable, THB, for observation 1365, subject 3921, is not available. Second, Lustick and Shimp [1] state that subject 3935 may have been killed by a combination of high torque along the Y axis and high force along the X axis; the subject being compromised on run 1362 and finally killed on run 1363. This suggests that observations 1362 and 1363 may not be homogeneous with the rest of the data set.

Therefore, all models that include the THB variable were estimated without observation 1365. Further, all models were estimated with and without observations 1362 and 1363 to observe the differences in the resulting models and statistics. For reference purposes, a data set that contains observations 1362 and 1363 will be referred to as an A data set; otherwise the data set will be referred to as a B data set. For a specified number of variables, that model which yielded the smallest -2 log likelihood value was selected as the best. As can be seen from Figure 2, the best one-variable, two-variable, and three-variable models, estimated from data set A, are based on respectively,

(1) FHC

(2) THB, FHC

and (3) THB, FHA, FHC.

Figure 3 implies essentially the same results for data set B. Since these models are nested, the relative contribution of variables FHC, THB, and FHA may be tested in that order.

Variable Set	-2 Log Likelihood
Constant Only	29.10
THB	22.67
FHA	21.37
FHC	10.64
THB, FHA	20.09
THB, FHC	10.10
FHA, FHC	10.53
THB, FHA, FHC	10.08

THB denotes peak torque around the anatomical Y axis

FHA denotes peak force along the anatomical X axis

FHC denotes peak force along the anatomical Z axis

Figure 2: Head Dynamic Response Variable Sets and Associated -2 Log Likelihood Values for Data Set A

Variable Set	-2 Log Likelihood
Constant Only	25.46
THB	13.51
FHA	13.04
FHC	0.00
THB, FHA	0.06
THB, FHC	0.00
FHA, FHC	0.00
THB, FHA, FHC	0.00

THB denotes peak torque around the anatomical Y axis

FHA denotes peak force along the anatomical X axis

FHC denotes peak force along the anatomical Z axis

Figure 3: Head Dynamic Response Variable Sets and Associated -2 Log Likelihood Values for Data Set B

Figures 4 and 5 are summaries of the relevant test procedure. In the first stage, for both data sets A and B, FHC was tested to determine whether it significantly improved the model which assumed a constant probability over all values of the torque and force variables. Data set A yielded an observed chi-square statistic of 18.46, which is statistically significant at the 0.0000^{+} level. Data set B yielded an observed chi-square statistic of 25.46 which is significant at the 0.0000^{+} level. Thus, both data sets indicate that FHC significantly contributes to fatality prediction.

The second stage of model testing considered the addition of another variable to the model which included only FHC. Since the model based on THB and FHC is the best two variable model, the effect of adding THB to the model was examined. Including the THB variable resulted in observed chi-square statistics of 0.54 for data set A and 0.00 for data set B, both of which are not statistically significant. Finally, the model based on all three variables THB, FHA, and FHC, when tested against the model based on FHC only, resulted in statistically insignificant chi-square statistics of 0.56 for data set A and 0.00 for data set B.

Thus, based on both data sets A and B, a prediction model which includes only the FHC force variable is "best" as previously defined. The resulting "best" model, estimated from data set A, is given by

$$\text{Model A:} \quad \hat{P}(\text{FHC}) = \{1 + \exp[-(-7.3705 - 0.10721(\text{FHC}))]\}^{-1}$$

The resulting "best" model, estimated from data set B, is given by:

$$\text{Model B:} \quad \hat{P}(\text{FHC}) = \{1 + \exp[-(-281.42 - 3.7902(\text{FHC}))]\}^{-1}$$

Figures 6 and 7 show a comparison of observed probability (i.e., 0 or 1)

Test 1: FHC against Constant Only

$$L_1 - L_2 = 29.10 - 10.64 = 18.46 \text{ (1 d.f., } p = .0000^+)$$

Significant

Test 2: (THB, FHC) against FHC

$$L_1 - L_2 = 10.64 - 10.10 = 0.54 \text{ (1 d.f., } p > .50)$$

Nonsignificant

Test 3: (THB, FHA, FHC) against FHC

$$L_1 - L_2 = 10.64 - 10.08 = 0.56 \text{ (2 d.f., } p > .50)$$

Nonsignificant

THB denotes peak torque around the anatomical Y axis

FHA denotes peak force along the anatomical X axis

FHC denotes peak force along the anatomical Z axis

Figure 4: Testing the Significance of the Head Dynamic Response Variables Using Data Set A

Test 1: FHC against Constant Only

$$L_1 - L_2 = 25.46 - 0.00 = 25.46 \text{ (1 d.f., } p = .0000^{+})$$

Significant

Test 2: (THB, FHC) against FHC

$$L_1 - L_2 = 0.00 - 0.00 = 0.00 \text{ (1 d.f., } p > .50)$$

Nonsignificant

Test 3: (THB, FHA, FHC) against FHC

$$L_1 - L_2 = 0.00 - 0.00 = 0.00 \text{ (2 d.f., } p > .50)$$

Nonsignificant

THB denotes peak torque around the anatomical Y axis

FHA denotes peak force along the anatomical X axis

FHC denotes peak force along the anatomical Z axis

Figure 5: Testing the Significance of the Head Dynamic Response Variables Using Data Set B

Run Number	Subject Number	Observed Probability	Predicted Probability	FHC
LX1081	A03921	0	0.00069	-0.8
LX1899	A04101	0	0.00165	-9.0
LX1083	A03921	0	0.00169	-9.2
LX1898	A04101	0	0.00184	-10.0
LX1086	A03921	0	0.00218	-11.6
LX1085	A03921	0	0.00267	-13.5
LX1890	A04101	0	0.00273	-13.7
LX1082	A03921	0	0.00297	-14.5
LX1084	A03921	0	0.00297	-14.5
LX1087	A03921	0	0.00297	-14.5
LX1364	A03921	0	0.00349	-16.0
LX1889	A04101	0	0.00535	-20.0
LX1892	A03948	0	0.01909	-32.0
LX1900	A04101	0	0.01909	-32.0
LX1901	A04101	0	0.03219	-37.0
LX1891	A03943	0	0.04383	-40.0
LX1902	A04101	0	0.07271	-45.0
LX1362	A03935	0	0.07271	-45.0
LX1359	A04099	0	0.08028	-46.0
LX1903	A04101	0	0.09760	-48.0
LX1363	A03935	1	0.09760	-48.0
LX1893	A03924	0	0.56012	-71.0
LX1894	A03933	0	0.58634	-72.0
LX1905	A04101	1	0.69663	-76.5
LX1365	A03921	1	0.80549	-82.0
LX1895	A03951	1	0.86410	-86.0
LX1896	A03946	1	0.92365	-92.0
LX1360	A04099	1	0.99733	-124.0

Figure 6: A Comparison of Observed and Predicted Probabilities for Model A Based on Data Set A

Run Number	Subject Number	Observed Probability	Predicted Probability	FHC
LX1081	A03921	0	0.00000	-0.8
LX1899	A04101	0	0.00000	-9.0
LX1083	A03921	0	0.00000	-9.2
LX1898	A04101	0	0.00000	-10.0
LX1086	A03921	0	0.00000	-11.6
LX1085	A03921	0	0.00000	-13.5
LX1890	A04101	0	0.00000	-13.7
LX1082	A03921	0	0.00000	-14.5
LX1084	A03921	0	0.00000	-14.5
LX1087	A03921	0	0.00000	-14.5
LX1364	A03921	0	0.00000	-16.0
LX1889	A04101	0	0.00000	-20.0
LX1892	A03948	0	0.00000	-32.0
LX1900	A04101	0	0.00000	-32.0
LX1901	A04101	0	0.00000	-37.0
LX1891	A03943	0	0.00000	-40.0
LX1902	A04101	0	0.00000	-45.0
LX1359	A04099	0	0.00000	-46.0
LX1903	A04101	0	0.00000	-48.0
LX1893	A03924	0	0.00000	-71.0
LX1894	A03933	0	0.00020	-72.0
LX1905	A04101	1	0.99980	-76.5
LX1365	A03921	1	1.00000	-82.0
LX1895	A03951	1	1.00000	-86.0
LX1896	A03946	1	1.00000	-92.0
LX1360	A04099	1	1.00000	-124.0

Figure 7: A Comparison of Observed and Predicted Probabilities for Model B Based on Data Set B.

and predicted probability for data sets A and B respectively. In both of these figures the observations are arranged in order of increasing predicted probability.

C. PREDICTION OF CRITICAL ENVELOPES

Utilizing models A and B, a critical envelope for each can be predicted. This envelope defines those combinations of independent variables for which the predicted probability of injury (or fatality) is greater than some specified amount. This type of critical envelope corresponds to the type defined in a previous Desmatics technical report [4].

Suppose it were desired to restrict the variable values to a region in which the probability of fatality were less than some small probability p_0 (such as .01 or .05). In other words, the predicted probability $\hat{\underline{P}}(\underline{x})$ is desired to be less than p_0. From this, the three following equivalent inequalities follow:

(1) $\hat{P}(\underline{x}) \leq p_0$,

(2) $\{1 + \exp[-(\hat{\beta}_0 + \sum_1^k \hat{\beta}_i x_i)]\}^{-1} \leq p_0$,

and (3) $\hat{\beta}_0 + \sum_1^k \hat{\beta}_i x_i \leq \ln[p_0/(1 - p_0)]$.

For model A, the critical envelope at $p_0 = .05$ is

$$-7.3705 - 0.10721(\text{FHC}) \leq -2.9444$$

or equivalently

$$\text{FHC} \geq -41.29.$$

For model B, the critical envelope at $p_0 = .05$ is

$$-281.42 - 3.7902(FHC) \leq -2.9444$$

or equivalently

$$FHC \geq -73.47 \ .$$

Thus, the probability of fatality is predicted to be less than 5% if the magnitude of the force along the negative anatomical Z axis is less than 41.29 and 73.47 kilograms for models A and B respectively. Here it is easy to observe that the exclusion of observations No. 1362 and No. 1363 have a large effect on critical envelope prediction.

III. SUMMARY AND DISCUSSION

The formal statistical analyses of the data on the twenty-eight Rhesus monkeys in conjunction with previous results [4] indicate that, for models using Rhesus dynamic response, the one employing only the FHC variable (the force along the anatomical Z axis) is the best model for predicting fatality (injury). However, it should be recognized that the total amount of data used was small and that there were two observations about which some questions exist.

For both data sets A and B, the "nested" model testing indicates that the peak torque around the anatomical Y axis, THB, and the force along the anatomical X axis, FHA, do not contribute significantly to fatality prediction. The testing also shows that the FHC variable contains the most information of the three variables under consideration whether or not observations No. 1362 and No. 1363 are included.

For observation No. 1363 all estimated models predict low probabilities of fatality, even though this observation corresponds to a fatality. Although there is a possibility that this observation is an outlier in the data set, it may be that THB and/or FHA are also important predictor variables, but that there is insufficient information on them, i.e., not enough observations where the THB and FHA values are high in the negative direction. If observation No. 1363 is indeed an outlier, then the "best" model estimated from data set B, model B, should be the accepted model based on the experimentation completed thus far. However, if observation No. 1363 is a relatively rare (but important) observation, then model A is to be the preferred, parsimonious prediction model.

At present, it would be premature and unwise to conclude that observations No. 1362 and No. 1363 are spurious and therefore remove them from the data set. It should be noted that the sled profile variables provide almost perfect predictors of fatality for all the observations, including No. 1362 and No. 1363. (See [4].) This suggests that these observations should not be regarded as outliers. Thus, if a model were to be used at present, model A would probably be the wisest choice. It should be beneficial, however, to attempt to extract optimal predictors from the dynamic response by the procedures outlined in a forthcoming report [6].

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This technical report describes the construction of impact acceleration injury prediction models from a set of twenty-eight $-G_x$ accelerator runs involving Rhesus monkeys with securely restrained torso and unrestrained head. Peak torque and force variables measured during these runs were used to predict injury likelihood. The relative contribution of these variables was examined with respect to the original and a modified version of the data set. Two possible prediction models were used to

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construct two critical envelopes, i.e., those values of the variables for which the predicted probability of injury (or fatality) is less than or equal to some specified probability. The preferred model was identified and discussed.

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